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ABSTRACT

The ability of the microcomputer to compile voluminous and detailed measures of students' learning activities automatically has seemingly outpaced the ability of commonly-used data analysis methods to make effective utilization of this wealth of potentially useful information. This study explores the use of computer-based quantitative methods, including sequence comparison and cluster analysis, to explore the learning behavior of high school students using computer software during assigned classroom problem-solving exercises that involve data analyses through graphing. Behavioral sequence data, that is, steps used in the individual student's solution process, were recorded automatically for a very large sample of high school students, along with extensive anecdotal observations and unstructured interviews during the course of normal classroom activities. The most noteworthy result was an indication of the overall persistence and resourcefulness of the students, in that the percentage using unorthodox, yet effective, approaches to solving the graphing problems was unexpectedly high. (32 references) (JJK)

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**Exploratory Problem Solving with a Graphing Application:
Semi-automated Analysis of Student Performance Data**

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Overview

The ability of the microcomputer automatically and inobtrusively to compile a large volume of highly detailed recordings of students' actions has thus far largely outstripped the ability of commonly-used analytic methods to make sense of this wealth of potentially useful information. This study explores the use of computer-based quantitative methods, including sequence comparison and cluster analysis, to help make sense of a large volume of automatically gathered data. The educational phenomenon examined is the behavior of high school students using microcomputer software to solve problems involving scientific data analysis through graphs.

Original scientific graphing software, *CAPGraph* (Jackson, Berger, & Edwards, 1990), was developed for use by inner-city high school students enrolled in a computer applications program. Most of these students had little or no previous exposure to the design and interpretation of graphs in mathematics or science courses. Behavioral sequence data ("traces" of solutions to a set of scientific data analysis problems) were recorded automatically for a very large sample of these students, along with extensive anecdotal observations and unstructured interviews during the course of normal classroom activities.

The core of the methodology explored here is a family of algorithms known as sequence comparison techniques (Sellers, 1974; Kruskal, 1983; Kruskal & Sankoff, 1983), previously used almost exclusively in the natural and information sciences (e.g., Bradley & Bradley, 1983; Coggins, 1983; Erickson & Sellers, 1983; Smith & Waterman, 1980, 1981). I have developed software (Jackson, 1990) implementing several variations of these algorithms, along with some more traditional modes of analysis of

behavioral data, such as the compilation of frequency counts of individual actions. The output of such analyses can serve as an input to more well-known quantitative methods, most notably several types of hierarchical cluster analysis, which can help to group together similar patterns of actions as an aid to their ultimate qualitative interpretation. The software also implements several clustering algorithms (Aldenderfer & Blashfield, 1984; Hartigan, 1975; Johnson, 1967; Lance & Williams, 1966; Wishart, 1969), structuring the output in such a way that a larger number of cases may more effectively be handled than with most commercially available statistical software packages (e.g., *SPSSx*TM, *Systat*TM).

I first compared and contrasted the results of various versions of sequence-comparison-based analysis with each other and with those from more customary methods, both qualitative and quantitative, for a relatively small subset of the available data. An original, "balanced" distance measure, defined as a composite of a related pair of similarity and dissimilarity measures, performed especially well by the criterion of correspondence to painstaking qualitative judgments (Jackson, 1990).

A refined version of this method of analysis was then applied to a much larger body of data, incorporating both more students and a wider variety of problems. Specific distinctive patterns of computer commands common to many students and/or problems were identified, providing *ex post facto* evidence of the validity of the methodology and suggesting areas of concern for future revisions of graphing software and its instructional use.

The concluding discussion below relates the sequence comparison-based, semi-automated methodology to its philosophical underpinnings. This research approach has clear implications for several contentious issues in educational research: interpretive vs. scientific attitudes; naturalistic vs.

laboratory settings; hypothesis generation vs. hypothesis testing; insider's vs. outsider's perspective; subjective vs. objective decision processes; and computer vs. human capabilities. I also note several parallels with some recent methodological debates in two interrelated natural science fields, systematic biology and paleontology, which are likewise concerned with the scholarly description and explanation of diversity.

Methodological Observations

The data analytic goal in this study was to group together sequences of actions which are similar as a whole, for the purpose of describing the variety of interpretable overall strategies or approaches which students seem to be using in the computer-assisted problem-solving task.

Sequence comparison methods, combined with cluster analysis, can achieve this goal for data in the form of behavioral trace sequences. For a general introduction to sequence comparison and a detailed rationale for its use, see Berger & Jackson (1990).

Cluster analysis as a heuristic tool for describing diversity has been largely overlooked in educational research. From the perspective of the positivist paradigm of behavioral research, the search for commonalities between cases is seen as inherently less valuable than seeking to establish relationships between variables (Q-analysis vs. R-analysis, Bailey, 1983).

As one quantitative research theorist from the field of sociology summarizes the situation:

Many [researchers], including both those who espouse deduction and those who espouse induction, feel that explanation consists of seeking correlations between a dependent variable and one or more independent variables...Some...see [the grouping of similar individuals] as an exercise in pure description, as contrasted with explanation, and thus not worthy of too much attention (Bailey, 1983, pp. 264-265).

The synonyms for cluster analysis used throughout the statistical and methodological literature, such as "automatic classification" and "unsupervised learning," are pejorative descriptions in the minds of many. The implication is that the researcher who uses these techniques is abdicating an important aspect of professional responsibility to a computer.

This is not true, however, when algorithmic methods of analysis are used selectively, for specific and limited purposes. The memory-intensive process of non-visual pattern recognition based on a large body of data is a prominent weakness in the capabilities of the human mind. Basic cognitive psychology research has shown (Anderson, 1985) that this is particularly true when the patterns in the data are unfamiliar, unexpected, and/or out of context, or when the optimal organization of the data according to gestalt principles is problematic. Since the investigation of students' thinking about graphing and of the processes of solving problems using application software are still very much in an exploratory mode, these conditions describe the present situation well.

Cluster analysis differs from most purely qualitative, subjective description, however, in that it is "formal, planned, purposeful,..." with a definite principal function, that is, "...to name, to display, to summarize, to predict, *and to require explanation.*" (Hartigan, 1975, pp. 1, 6; italics added) Employed in an appropriate context, it can be a powerful link between quantitative and qualitative reasoning and rhetoric:

While statisticians think in terms of correlates of a dependent variable, most... theorists, and virtually all of the lay public, think in terms of the actions of persons....Now the emphasis has been switched from the analysis of variables to the analysis of the actions of individuals (objects). It is individuals who [act]. Thus, it can be argued that to understand [their actions] truly, a model is needed that focuses upon objects (Bailey, 1983, p. 265).

These quantitative analytic methods are effective as a way to render large amounts of data more manageable, but should be viewed as a supplement and aid to more subjective approaches rather than as a replacement for them. Subject matter expertise and first-hand classroom experience on the part of the researcher are essential to judgments about both the most appropriate coding of data for input to the quantitative analysis and the interpretation of its output.

Anecdotal observations during class sessions had provided occasionally vivid glimpses of the way that students think about graphs and graphing and of how the use of flexible and powerful computer software can facilitate valuable experience with this important science process skill. The recording, comparison, and characterization of their patterns of behavior did not bring to light any truly emergent phenomena not visible on a smaller, closer, more intimate scale. The results of the analysis of this data did, however, give a much broader and more comprehensive overview of which ideas and approaches are typical of larger numbers of people and which are largely idiosyncratic.

A point which deserves emphasis is that the sequence comparison and cluster analysis methods used, despite their real complexity in some aspects, are theoretically highly generalizable to use with data from other subject matter areas. In an important sense, sequence comparison is a simpler entrée to the quantitative analysis of behavior than the more customary event frequency approach, because its treatment of the data is based solely on the structural properties of the sequences, rather than any subjective knowledge of the meaning or relative importance of the constituent events. As a practical matter related to programming of the analysis, it does not require a limited universe of possible codes to be

predefined, as would be necessary to allocate space for all possible variables in any frequency-based approach.

A crucial step in preparing data for analysis by these methods is that in which subjective decisions must be made about coding. This can be reduced to two general issues: what constitutes "data" at all, and what instances of relevant information are sufficiently similar as to be essentially the same. Typically, these are not easy judgments, but they must be made as a part of any empirical research study, regardless of methodology.

Results

Perhaps the most striking overall finding is the resourcefulness and persistence of these students. They were provided with a powerful and flexible tool enabling them to explore the effect of multiple alternatives in a science process skill area, graphing, which has traditionally been one in which time-and labor-intensive algorithmic procedures were rigidly applied to conform to a preordained model. Many instances of "intelligently naive" reasoning were noted in classroom observations (Edwards, Jackson, & Berger, 1990), but the suspicion remained that the most salient examples of inspired performance could be an unrepresentative sample of the experiences of the students as a whole. In surveying the clusters of behavioral sequences generated by the quantitative analysis, the number representing unorthodox but effective approaches to these graphing problems was unexpectedly high.

A more general way of characterizing the patterns of diversity among these students' actions may be provided by another recent study (Siegler 1988), also using cluster analysis as a heuristic device. Individual cases

generally fall into three general categories of classroom problem solvers, called (prosaically but clearly) good students, not-so-good students, and perfectionists. Good students have a high degree of relevant knowledge and skills, plus high standards ("stringent thresholds") for determining when an acceptable answer to an academic problem has been found.

Perfectionists set high standards for their academic work but show varying degrees of deficiency in their knowledge and skills. Not-so-good students show little evidence of either virtue.

The behavioral traces of the work of these inner-city students with *CAPGraph* certainly contain evidence of many misunderstandings of principles of graphs and data analysis, but suggest that there are many more perfectionists than not-so-good students among them. Many of the participating teachers were initially skeptical that their students, who were highly accustomed to rigidly prescribed classroom activities pursued according to highly specific stepwise instructions, could handle the responsibilities inherent in these comparatively open-ended problem-solving activities. The strong relationship of student achievement to teacher expectations is one of the great truisms of educational rhetoric, but is too often ignored in practice. The availability of tools such as computer graphing programs should be cause for teachers and curriculum designers in science and mathematics, especially in inner-city school districts, to rethink their preconceptions about the limitations on what students can accomplish and learn in the course of the experience of creative problem solving.

A consistent implication of the variety of approaches to graphing taken in many of the problems examined is that the specification of rigid, algorithmic rules of proper graphing practice is not a defensible approach

to teaching students about graphs. In the case of several of the problems analyzed, using a rule as an algorithm to be executed rather than a heuristic to suggest a first approach had two undesirable effects: first, yielding a wrong answer; second, precluding the exploration of other possibilities for graphical data analysis. Such "unauthorized experiments," although often inefficient and sometimes bizarre, provide a much more challenging and potentially educative experience for the participating students. Very often generalized rules are presented in the context of science classes uncritically, as just another part of a set of "cookbook" laboratory instructions, because a trial or discussion of alternative approaches would be too time-consuming. The kinds of "thought experiments" facilitated by appropriately designed software give students a taste of a kind of approach to scientific data analysis which is more common in "real world" situations: the consideration of multiple options and the stepwise refinement of the one eventually chosen.

Discussion: Approaches to Educational Research

By placing such a great emphasis on the value of both algorithmic, computerized data analysis and subjective judgments which can only be made by a researcher with firsthand experience in an educational setting, this study is certainly vulnerable to charges of unreasonable methodological eclecticism. I believe, however, that there is a coherence to this approach which makes it more valuable, for this exploratory type of research, than the prescribed methods of the orthodox forms of either the positivistic "behavioral science" or qualitative "human science" approaches.

This study is more an exercise in description than in explanation, of hypothesis generation rather than hypothesis testing. Despite hours spent in the past with the students whose efforts are reflected in the trace sequences, they are no longer available, and the immediate task has been to find a way to describe the diversity of approaches and thought patterns implied by the disembodied data which remain.

A similar research situation exists in some of the natural sciences, notably in systematic biology and paleontology, in which much of the day-to-day work of scientists consists of producing and describing classifications of the observable diversity of the world. These closely related fields are often ignored in general discussions of the philosophy of scientific research, seemingly because their descriptive (vs. experimental) nature makes them conform much less easily to the rationalistic, positivistic ideal held by many practitioners of the "exact sciences" (e.g., chemistry and physics).

A survey of the three major methodological schools of thought in biological taxonomy can provide a useful comparison and contrast to the raging debate over research methods in education. The venerable orthodoxy is known as evolutionary systematics, and is perhaps best exemplified by the classic codification of Simpson (1961), in which classification and description are characterized as "really a combination of a science, more strictly speaking, and an art" (p. 110). In this approach, highly subjective judgments are made as to the relative importance of a few variables among the many for which differences between individuals or groups may be observed. A hierarchical classification scheme is then developed in which, most typically, each branching point is defined with reference to a small number of key characteristics.

A more recently developed method, numerical taxonomy, uses cluster analysis based on data for a very large number of variables which are not statistically weighted in any way. There is no provision for arguing with the plausibility or utility of the results, and the only subjective judgments which enter into this method are those regarding the the coding of data and the choice of variables to be included. The stated goal of this school of researchers is to make the process of description and classification "more standardized, repeatable, rigorous, and objective" (Sneath & Sokal, 1973, p. 49).

A third and most recently appearing approach, cladistic taxonomy, was developed by those wary of both the rampant subjectivity of evolutionary taxonomy and the fact that the computerized algorithmic methods of numerical taxonomy are "far removed from the general notion that any 'observation'...constitutes a hypothesis" (Eldredge & Cracraft, 1980, p. 8). A clade is a group defined as any biological species and all of its direct evolutionary descendents. A cladist takes into account a wide variety of variables, and may even use the output of numerical taxonomic cluster analyses as a heuristic device. The cladistic approach adds an additional condition to the ultimate task of classification, however - similarity relationships between subgroups of a clade, since they are inferred to represent evolutionary lineages, must be definable and understandable in terms of a relatively small number of nearly exact similarities. The break with tradition lies in the commitment to let the data themselves suggest all possible groupings, before critically evaluating such emergent patterns subjectively, in relation to theoretical concerns.

In contrast to the history of educational research, in systematics and paleontology it was qualitative methods which were first firmly ensconced,

fought off a challenge from quantitatively-oriented critics, and ultimately had their logic incorporated into a new, synthetic method. I see the kind of combination of research methods used in this study as in the same spirit as the work of the paleontologists who developed the concept of cladistic taxonomy.

Weizenbaum (1976), a computer scientist with the heart of a philosopher, draws a crucial distinction in introducing his ideas about the capabilities and limitations of what Simon (1969), a polymath and positivist, has called "the sciences of the artificial":

Beginning perhaps with Francis Bacon's misreading of the genuine promise of science, man has been seduced into wishing and working for the establishment of an age of rationality, but with his vision of rationality tragically twisted so as to equate it with logicality. Thus have we very nearly come to the point where almost every genuine human dilemma is seen as a mere paradox, as merely apparent contradiction that could be untangled by judicious applications of cold logic derived from a higher standpoint (Weizenbaum, 1976, p. 13).

Logicality is the area in which the computer excels, and its use is appropriate so long as it is truly in the service of rationality, the more inclusive capability truly possessed only by the human mind. There are problems and issues, educational ones prominent among them, which would not disappear even if an essentially unlimited amount of computing power were applied to a perfectly complete and accurate record of objective information about every aspect of the phenomena which give rise to their perception.

An incisive critique of the view of educational research as a science has come from those advocating small-scale, qualitative studies emphasizing "participant experience" and "bodily presence in the field" as indispensable aspects of "a research method which is dialogically based on respect for the child," which "moves interpretations closer to real life and its

consequences" (Beekman, 1986, p. 39). At its simplest, this philosophical tradition emphasizes that the value of research is closely tied to a highly personal level of narrative communication between researcher and audience: "...Sensitivity, insight, and the ability to tell stories are all required. None of these seems a necessity for the mainstream positivist researcher these days" (Beekman, 1986, p. 44).

This view has been summarized as favoring research which is "'illuminative' and 'qualitative' rather than 'statistical' and 'quantitative'" (Hamilton, et al., cited in Carr, 1983, p. 35). I strongly agree that "illumination" should be the goal, but I question the assumption that statistical methods have no place in the process of generating accounts of educational phenomena which can be meaningful in the concrete as well as in the abstract.

What, exactly, is the stock in trade of an educational researcher, as opposed to an unusually perceptive and reflective (*sensu* Schön, 1983) teacher? The answer lies in the well-known phenomenon often expressed as "not being able to see the forest for the trees":

...there may be factors operative in educational situations which remain opaque to the self-understandings of practitioners and cannot be explained by reference to their intentions and beliefs.

...What is required, therefore, is a view of educational research which is 'interpretive' in the sense that its theories are grounded in the perspectives of educational practice and 'scientific' in the sense that these theories provide a coherent challenge to the interpretations which practitioners actually employ (Carr, 1983, pp. 38, 39).

It is precisely such a perspective which can be gained from a study of large-scale data such as behavioral traces *in conjunction with* the insights gained from teachers or students, or from the researcher's own experience as a "participant observer."

A researcher is an "outsider," and typically lacks the wealth of experiences and perhaps the immediate perceptive abilities of an "insider" such as a teacher. An insider, however, often "sees the image of anything as being the sum of its details," and "can conceive of the whole of anything only by remembering this event and that event and piecing them together in a succession of images" (James, 1984, p. 6). In seeking to understand the world, however, a researcher has the unique luxury of "...step[ping] back from it and study[ing] it *intensely and minutely, but from a distance,*" (James, 1984, p. 6, italics added). In accepting the limitations of outsider status, a researcher should not lose sight of the positive aspects of his or her position:

But perspective can be gained only when details are lost. A sense of the size of everything and the relationships between everything - this can never be put together from details. For the most essential fact of a forest is this: The forest itself is immensely larger than anything inside of it. That is why, of course, you can't see the forest for the trees; each detail, in proportion to its size and your proximity to it, obscures a thousand or a million other details.

I've never said, never thought, that it was *better* to be an outsider than it was to be an insider, that my view of [reality] was better than anyone else's. It's different; better in some ways, worse in some ways. What I have said is, *since* we are outsiders...let us use our position as outsiders to what advantage we can (James, 1984, pp. 6,8).

In a classroom where students are engaged in problem-solving activities, a teacher or participant observer can only talk with or closely observe a few students at a time, and can even superficially observe only one class at a time. The applicability of this point of view to educational research is not diminished by the fact that James' chosen field of expertise happens to be baseball.

Recording detailed research data does not have to mean that one's view of the participating students lacks "respect" or is necessarily severely limited by "theoretical preconceptions...prejudices and overly abstract

suppositions" (Beekman, 1986, p. 44). An exploratory study such as this one seeks initially only to characterize the thoughts and actions of students, not to judge them based on a model of ideal thought or behavior. This is what Schön (1983) had called "giving them reason," working under the implicit assumption that even sequences of actions which are apparently random represent purposeful activity on the part of the people being observed for research purposes. Purposeful, disciplined qualitative observations can be carried out by teachers during class sessions, and if recorded in sufficient detail are always open to the possibility of quantification or analytic treatment in the future (Minstrell, 1989).

In sum, a methodologically eclectic approach to classroom research has the potential to provide both of the kinds of results normally associated with each extreme on the spectrum: on the one hand, interesting narrative accounts of educational phenomena which can capture the imagination and hold the interest of practitioners, and on the other, quantitative summary data giving some indication of the degree to which the narrative accounts are typical of more than a few students:

..to do more qualitative or naturalistic research does not mean that in some doctrinaire way you stop counting, stop using statistical tests, stop being as precise as you possibly can when precision is possible. What it simply means is that you don't do research with one hand tied behind your back (Shulman, 1985, p. 445).

An eclectic research style is an expression of humility, not of hubris. It simply recognizes the value of the interpretive as well as the scientific outlook, both naturalistic and laboratory settings, hypothesis generation as a prerequisite to hypothesis testing, both subjective and objective contributions to decision processes, the unique advantages of both the insider's and outsider's perspective, and the complementarity of computer

and human capabilities. It is an acceptance of the fact that good research should both listen to and express itself in multiple voices.

The best use of these methods would not be in a wholly secondary data analysis such as this one, but rather interleaved with qualitative classroom observations from day to day. If coding (as well as raw data collection) were efficient enough, analysis of trace data by sequence comparison and cluster analysis could be performed immediately following each class session or day. Behavioral patterns whose interpretation is problematic could point to particularly fruitful questions which might be directly asked of the students during later sessions in order to better understand the thinking and motivation behind their actions. In this way quantitative analysis could not only supplement but also redirect and inform qualitative investigations.

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